Simulation of Mechanical Behavior of Agglutinates

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Abstract

Due to lack of "real" lunar soil or even lunar simulant, it is difficult to characterize the interaction between lunar soil (or simulant) with different surfaces that are involved in excavation and processing machinery. One unique feature possessed by lunar soil is the agglutinates produced by repeated high-speed micrometeoroid impacts and subsequent pulverization[1 and 2]. The large particles are impacted by micrometeoroids [Fig.1] and pulverized to produce finer particles. This process continues until there are no more "large" particles left on the surface of the moon. Due to high impact speed, the impact melting process fuses fines to make agglutinates such as shown in Fig. 2.

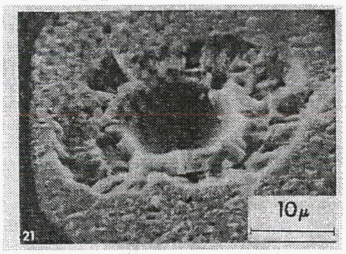


Figure1. Micrometeoroid impact crater

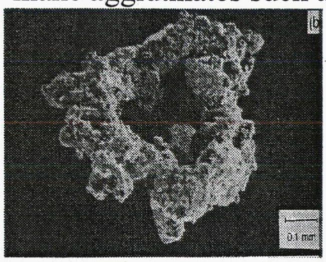
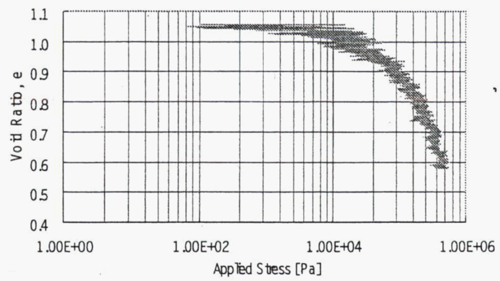


Figure 2. Agglutinate



The PFC2D™ is a discrete particle simulation code that allows simulating discontinuous behavior of particle assemblies, which can eventually lead to a large-scale failure. Dave Carrier et al. conducted one-dimensional oedometer tests and the compressibility measurements on lunar soil samples [3]. We will present a series of simulation results and movies will be shown to indicate brittle behavior of each individual agglutinate and also similar compressibility charts shown by Carrier et al. [3]. Fig. 3 shows our preliminary result of the simulated oedometer tests.

Acknowledgements

We acknowledge that this project is partially supported by NASA NNM05AA88C. Dr. Nakagawa acknowledges stimulating conversations with Dave McKay, Dave Carrier and Larry Taylor that inspired this work.

References

1. D.S. McKay, R.M.Fruland and G. H. Heiken, "Grain size and the evolution of lunar soils". Proceedings of the Fifth Lunar Conference (Supplement 5, Geochmica et Cosmochimica Acta) Vol. 1 pp.887-906 (1974).
2. W.W. Mendell and D.S. McKay, "A Lunar Soil Evolution Model". The Moon 13 (1975) 285-292.
3. Lunar Sourcebook, edited by G.H. Heiken, D.T. Vaniman, and B.M. French, 1991, Cabmbridge University Press.

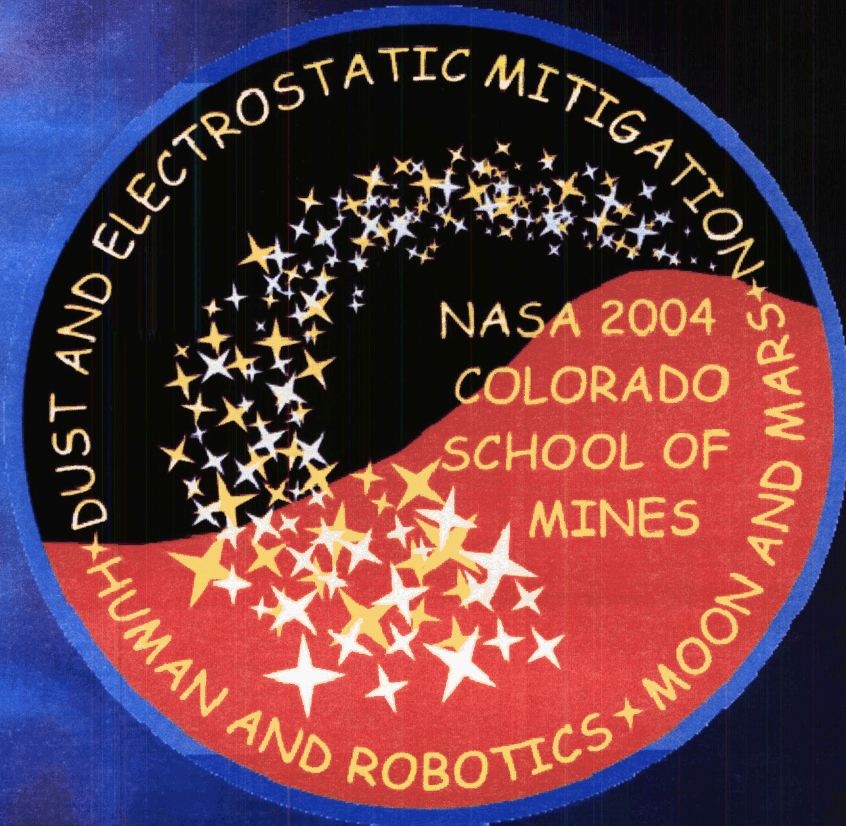
International Lunar Conference

September 18-23, 2005, Toronto, Canada

Simulation of Mechanical Behavior of Agglutinates in the context of NASA BAA Project "DUST"

Masami Nakagawa: Colorado School of Mines

“Project Dust”



"Mitigation of Dust
and
Electrostatic Accumulation
for Human and Robotic Systems for Lunar
and Martian Missions”

Allen Wilkinson

Researcher Capabilities Summary

NASA Glenn Research Center

Science themes over the years:

- Surface Raman spectroscopy from free electron metals
- Raman spectroscopy as a concentration probe
- Liquid-vapor critical phenomena, P.I. on 3 shuttle exp'ts
- Microscopy of sub-correlation length critical point fluctuations
- Stat. Mech. of Fluids, Molecular Dynamics simulations
- Entropically driven self-assembly of colloids, photonics & microscopy involved
- Granular Materials, force chains & fluctuations as 'the' dynamical observables, image processing chains

Member of modeling sub-group

- Understand the physics of inter-particle interactions from classical interactions to Nose-Hoover terms in particle equations of motion.
- Able to program and run code on PCs to mainframes/clusters
- No publication history in dust modeling, given past NASA work.
- ??

It is about *what you can do!*

Physical Surface Properties

Material Properties

Moon & Mars Environment-----HARSH!

Mechanical Properties

Material Properties or Geotechnical Index Properties

1. Particle Size Distribution
2. Specific Gravity
3. Bulk Density and Porosity
4. Relative Density

Mechanical Properties

1. Compressibility
2. Shear Strength
3. Bearing Capacity
4. Slope Stability
5. Trafficability

ISRU-Granular Materials-Dust

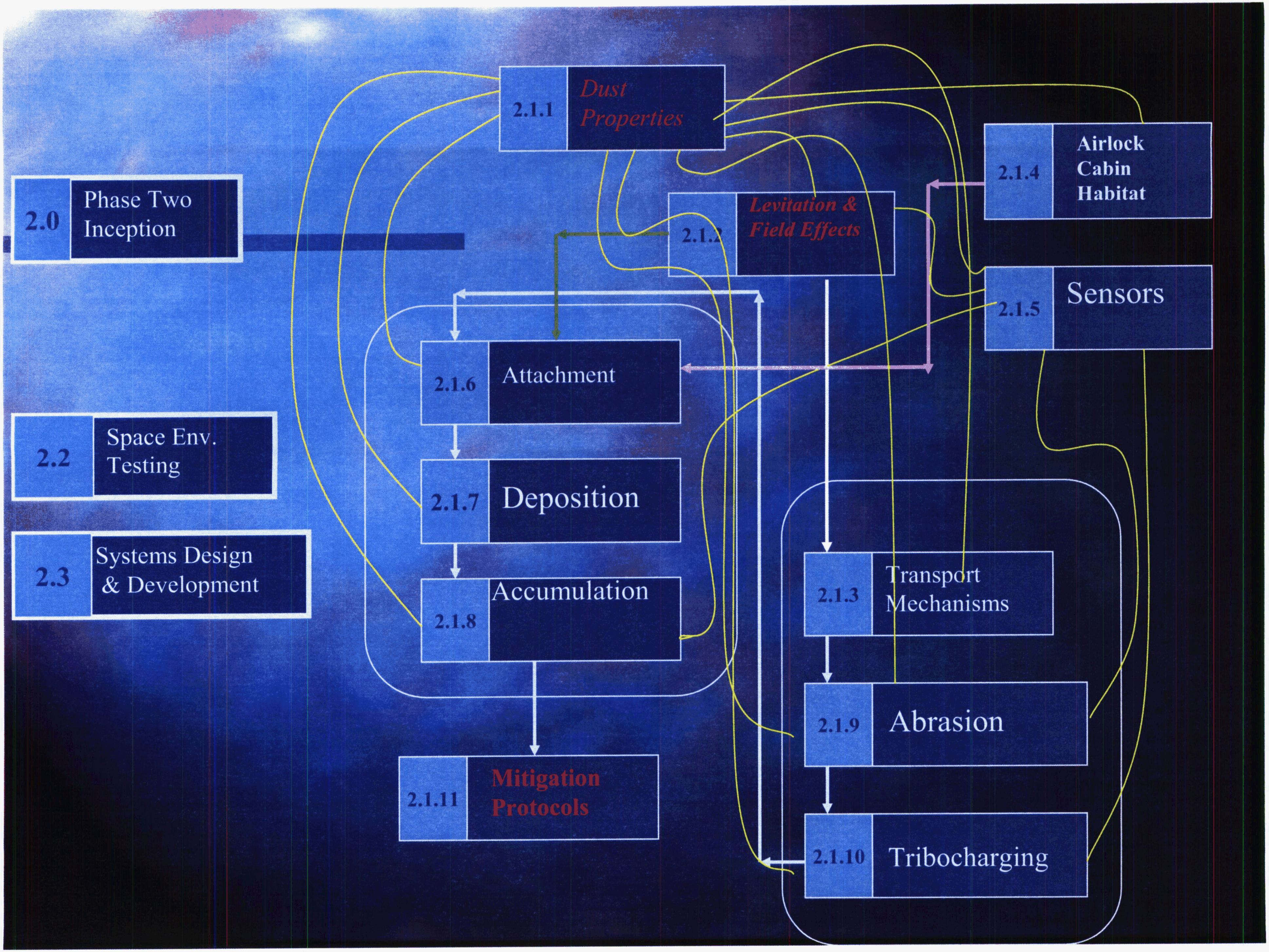
Two Main Thoughts:

1. How can "granular materials" research really help Space Exploration ?

2. "Dust Research" as a subset of Granular Materials Research

ISRU and Dust

ISRU Processes	Impact
Excavation	Adhesion
Solar Power	Dust coating and abrasion reduces cell efficiency
Electronics	Grounding
Separation	Electrostatic and/or magnetic separation



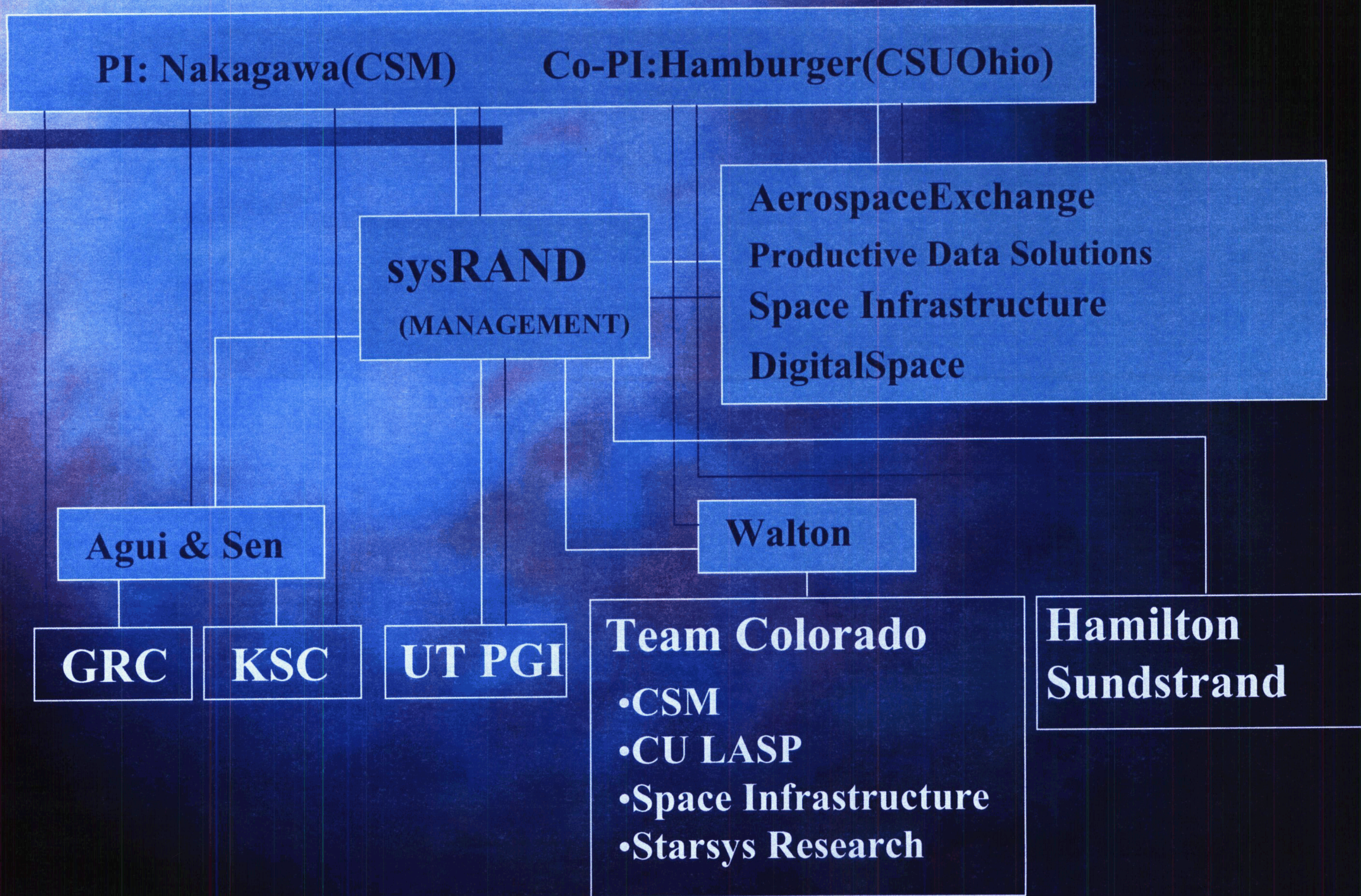
2.0 Phase Two Inception
2.1.1 Dust Properties
2.1.2 Levitation & Field Effects
2.1.4 Airlock Cabin Habitat
2.1.5 Sensors
2.1.6 Attachment
2.1.7 Deposition
2.1.8 Accumulation
2.1.3 Transport Mechanisms
2.1.9 Abrasion
2.1.10 Tribocharging
2.1.11 Mitigation Protocols
2.2 Space Env. Testing
2.3 Systems Design & Development

Vulnerability Matrix

Subsystem / System	Air Filters	Rotating Shafts / Parts	Sliding Shafts / Parts	Optics / Solar Panels	Radiator / Reflector Panels	Pressure Seals	Charge Accum Surfaces	Electrical Connectors / Switches	
Spacesuits	✓	✓	✓	✓	✓	✓	✓	✓	
Airlocks	✓	✓	✓			✓	✓	✓	
Exploration Vehicles	✓	✓	✓	✓	✓	✓	✓	✓	
Habitats	✓	✓	✓	✓	✓	✓	✓	✓	
Manufacturing Plants	✓	✓	✓	✓	✓	✓	✓	✓	
Exposed Hardware		✓	✓	✓	✓	✓	✓	✓	
Robots and Remotes		✓	✓	✓	✓	✓	✓	✓	


C C A C S
CENTER FOR COMMERCIAL APPLICATIONS OF COMBUSTION IN SPACE
"Project Dust" Team
COLORADO SCHOOL OF MINES
LASP University of Colorado
Laboratory for Atmospheric and Space Physics
University of Tennessee
Planetary Geosciences Institute
Space Infrastructure, Inc.
GRAINFLOW DYNAMICS
PDS
Productive Data Systems
NASA
Glenn Research Center
Kennedy Space Center
Johnson Space Center
THE STATE UNIVERSITY of NEW YORK
SUNY
Department of Physics
Hamilton Sundstrand
A United Technologies Company
STARSYS
RESEARCH
sysRAND Corporation™

1) Organizational Responsibility Chart



Gary RODriguez
Capabilities Summary

sysRAND Corporation™

- Industrial Automation

  Ruggedized controls for nearly any application, data acquisition and process control.
- Commercial & Military Avionics

  Performing systems architecture, analysis and design -- hardware and firmware. From *back-of-the-envelope* through production and onto the fleet.
- Space Commercialization and Development

  Reducing risk by translating technology into application-specific ruggedized products. Project Management, Definition and Realization.

- *Imbedded Controls*
- *Data Acquisition Systems*
- *Interfaces*
- *Custom Power Supplies*
- *Programmable Logic*
- *Firmware / Debuggers / Monitors*
- *Microprocessor-Based Applications*
- *Condensed-code regimes*
- *Parallel Systems / Communications*
- *Classic, Esoteric & Arcane Systems*
- *Reverse-Engineering*

Spiral Development

- Spiral 1: Crew Exploration Vehicle (CEV)
  - 2008: CEV demo
  - 2011: Unmanned CEV
  - 2014: First manned CEV
- Spiral 2: Human return to the Moon
  - No later than 2020 (as early as 2015)
  - Robotic missions to Moon
  - Short duration (7 day notional mission)
- Spiral 3:
  - Sustained human presence in space (longer lunar stays)
- Spiral n:
  - First human mission to Mars (2030 notional mission)
- Exploration Systems Research & Technology (ESR&T) Priorities
  - Technology Maturation Program (TMP)
    - Spiral 1 CEV
    - Spiral 2 Robotic & Human Lunar Return
  - Advanced Space Technology Program (ASTP)
    - Spiral 2 Human Lunar Return
    - Spiral 3 Sustained human presence
    - Spiral 3 Mars precursors and human missions

1.0 Phase I Project Statement of Work

1.1 Research & Technology Development

1.1.1 Dust Properties

1.1.1.1 Regolith Dusts

1.1.1.1.1 Define a specification for a comprehensive inventory of individual particle mechanical properties, including hardness and strength.

1.1.1.1.2 Define a specification for a comprehensive inventory of the bulk flow properties of powders and dusts in space exploration environments. Mechanical properties of interest here include friction, cohesion, adhesion, strength, *etc*.

1.1.1.1.3 Plan for determination of surface chemistry and trace chemicals in soils, both *in-situ* as well as attributes conducive to remote (satellite) sensing.

1.1.1.1.4 Connect the physical attributes of specific particles to optical and electromagnetic spectra (*ie*. chromatography).

1.1.1.1.5 Characterize the magnetic properties <45 μm fractions of lunar soil, using actual Apollo Mission soil samples. Ascertain both characteristics of attraction and repulsion in magnetic fields, and whether any polarization of particle patinas occurs.

1.1.1.1.6 Develop tests for additional characteristics of Lunar Regolith from Apollo Missions beyond those already in the literature.

1.1.1.1.7 Establish preliminary requirements for Lunar and Martian simulants.

1.1.1.1.8 Identify mechanisms unique to Luna and Mars which break down dust to finer particles.

1.1.1.1.9 Identify EVA activities which encourage the breakdown of dust to finer particles.

Plan for investigation of Lunar glass processes from high energy impact through agglutination and comminution into extremely fine-grained particles.

Planetary Geosciences Institute

University of Tennessee – Larry Taylor, Director

Our discovery of the High Magnetic Susceptibilities of the Dust fractions of the Apollo soils, due to the presence of ferromagnetic nanophase Fe^0, has presented possibilities for significant Lunar Dust Abatement Scenarios.

Research Members:

David Carrier, ScD (CE; MIT)
Lunar Geotechnical Institute; LUNAR SOIL ENGR

Jim Carter, Ph.D. (TX-Austin)
TX A&M; LUNAR SOIL SIMULANT SPECIALIST

Hap McSween, Ph.D. (Harvard)
Univ. Tennessee, MARTIAN SOIL SCIENCE EXPERT

Jack Schmitt, Ph.D. (Harvard)
Apollo17 Astrounut, LUNAR REGOLITH & DUST SCI/ENGR EXPERT

Larry Taylor, Ph.D (Lehigh)
LUNAR ROCK & SOIL SCI/ENGR & ISRU EXPERT

Tasks:

- ***Assess*** magnetic properties of the <50 μm fractions of lunar soil, using actual Apollo soils;
- ***Develop*** lunar soil nanophase Fe^0 simulants with different amounts of nanophase-Fe^0, which have similar magnetic properties for a variety of lunar soils;
- ***Design and Produce*** lunar soil simulants with approximate geotechnical conditions that have not only the appropriate nanophase-Fe^0 contents, but also other chemical & physical properties [e.g., glass contents], such that these form the basis for studies of the magnetic and electrostatic mitigation of lunar dust.
- ***Magnetic Experimentation,*** using both simulants and real Apollo soils, for various schemes of dust mitigation.

Colwell, Horanyi & Robertson

Plasma Laboratory Facilities

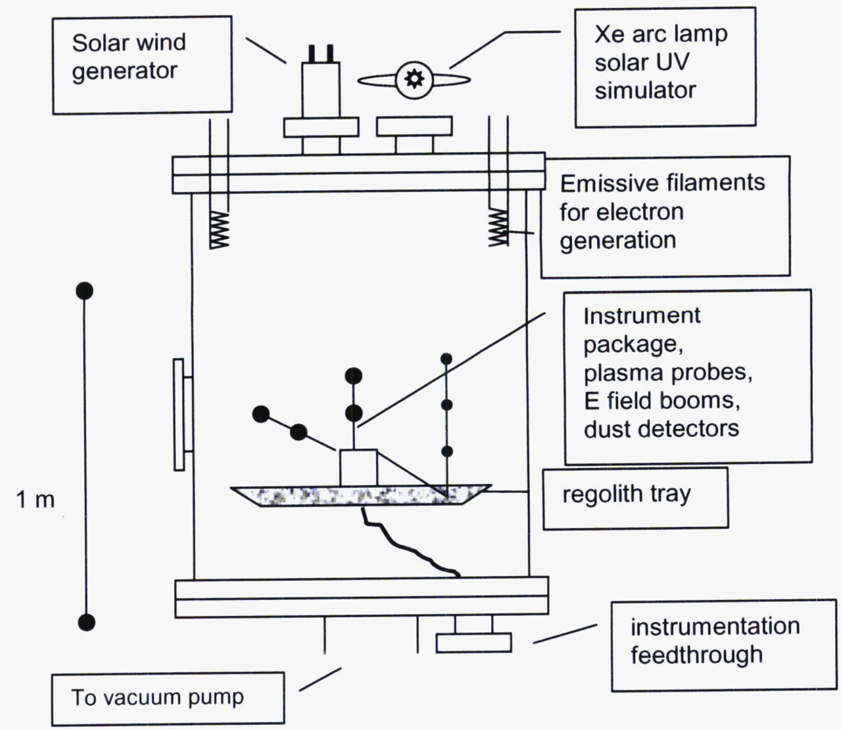
LASP-Univ. of Colorado

The CU Plasma Lab has three plasma devices for dusty plasma investigations.

The largest device, shown here, is planned for experiments on dust charging on the lunar surface.

The instrumentation for this device needs to be purchased and installed.

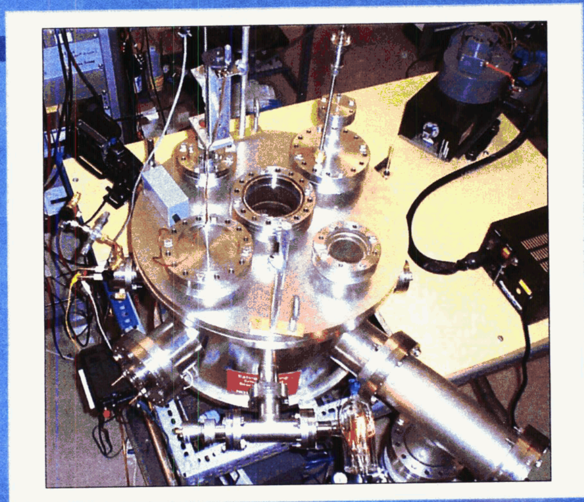
A smaller device, shown on the next slide, is currently being used to study horizontal transport of dust levitated in a plasma sheath over the surface.

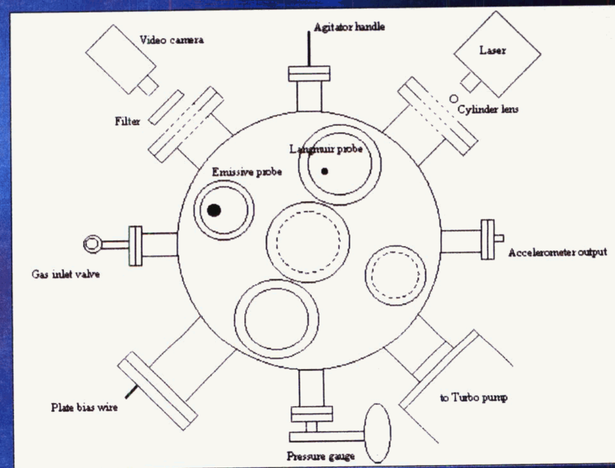


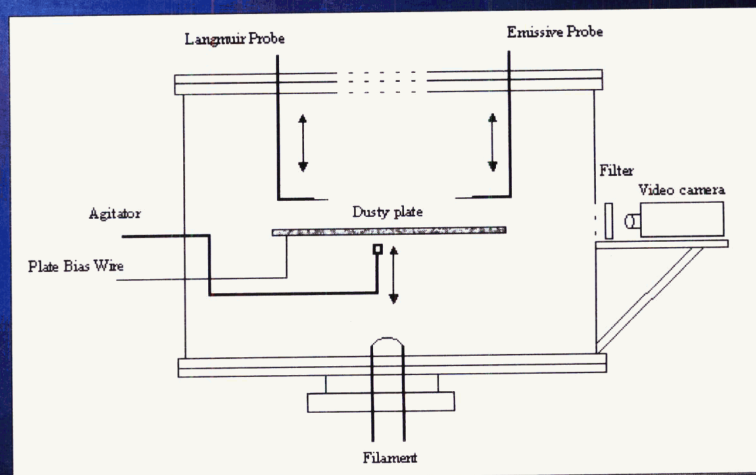
Schematic diagram of the **lunar surface environment simulator**. The one-sixth-scale instrument package is placed within a vacuum chamber 0.9 m in diameter and 1.2 m tall. The package rests on a tray of JSC-1 lunar regolith simulant. E-field booms are shown extending from the package. The small spheres are current collecting probes. Dust impact detectors are mounted at several locations on the surface of the instrument package.

Laboratory Facilities (cont.)

Small Plasma Device Currently in Use







Carlos Calle, Ph.D.

Researcher Capabilities Summary

ESPL at KSC

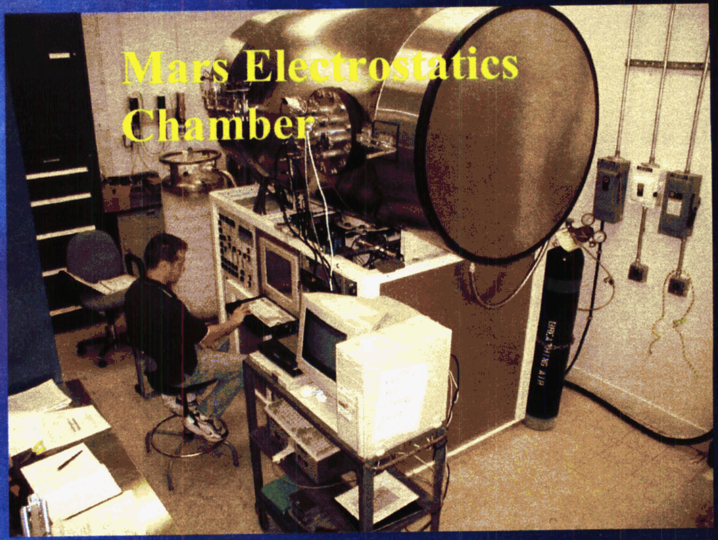
http://electrostatics.ksc.nasa.gov

The Electrostatics and Surface Physics Laboratory (ESPL)

KSC has been the lead NASA center for testing and evaluating the electrostatic properties of materials for more than 40 years. Materials are evaluated using surface resistivity, volume resistivity, corona and tribo charge decay, chargeability, capacitance loading, and spark incendivity.

The ESPL has co-designed the MECA Electrometer, a flight instrument slated to fly on the '01 lander (cancelled) designed to measure the triboelectric properties of the Martian surface.

Flight instrumentation can be tested in the Mars Electrostatics Chamber, a large fully-automated vacuum chamber which simulates the temperature, pressure and atmospheric constituents of Mars. Diurnal cycling can also be performed as a function of latitude.



The ESPL atmospheric-pressure plasma discharge treats the surface of materials to alter their electrostatics properties. Surface modifications are monitored using X-ray photoelectron spectroscopy.

The ESPL is developing technology to measure the size and charge of dust particles suspended in the Martian atmosphere by miniaturizing a commercially available device called the E-SPART developed by our collaborators at the University of Arkansas at Little Rock.

Carlos Calle, Ph.D.

Researcher Capabilities Summary

ESPL at KSC

http://electrostatics.ksc.nasa.gov

The ESPL has developed techniques to remove/repel dust from insulating surfaces using our Electrodynamic Screen technology. Originally developed in Japan in the 1970's, the ESPL has improved the technology by successfully demonstrating it under simulated Martian conditions without dielectric breakdown problems. This technology is currently at TRL 4 and work is currently being performed to apply this technique to solar panels, visors, and viewports.

The ESPL can address electrical breakdown properties of the Lunar/Martian environments and solve many electrostatics-related problems. Our scientists have extensive experience in electrostatics including: Paschen breakdown measurements, vacuum breakdown, dielectric breakdown of gases, dielectric strength of materials, dielectric permittivity and tribocharging of Martian dust simulant; pulsed high voltage discharges in liquids and gases, gaseous discharges such as corona, streamer corona, glow, brush and propagating brush discharges; glow discharge under Martian environmental conditions, corona, tribo and induction charging; free electron charging, electron beam charging, aerosol science, particle charging and discharging; electrostatic spray coating, electrostatic precipitation, static elimination, electrostatic instrumentation, high voltage equipment, vacuum equipment, gas handling, mixing and metering; and electrical bonding to earth.

The ESPL has recently completed a year long effort to evaluate the safety hazard associated with the Thermal Control System blankets for the Space Shuttle program and is currently evaluating similar hazards for the International Space Station.

In short, the ESPL is capable of consulting with a wide range of electrostatics issues but has an emphasis on space-based exploration issues.

Paul Hambourger

Researcher Capabilities Summary

Cleveland State University

Space Materials Lab

<u>Specifics</u>

- Combine work at Cleve. State and interaction with other Dust-ESD team members to develop improved weakly-conductive coatings for this application
- Deposit thin-film coatings as needed for use by myself and other members
- Measure and analyze electrical and optical properties before and after VUV exposure at Cleve. State and abrasion, etc by other members
- Report results to team to guide improvement
- Investigate ways to scale up weakly-conductive coating deposition
- Contribute physics expertise as appropriate

Paul Hambourger

Cleveland State University
Space Materials Lab

Researcher Capabilities Summary

- Vacuum deposition of thin-film coatings, including weakly-conductive materials
- Adaptation of coating techniques to specific materials
- Measurement of electrical transport properties of materials and coatings
- Measurement of optical transmittance and reflectance of materials and coatings
- Lab simulation of in-space vacuum ultraviolet (VUV) exposure
- Analysis and interpretation of electrical and optical properties of materials
- Development of improved weakly-conductive coatings
- Modeling of VUV and particle-radiation absorption and shielding in materials and coatings

Surajit Sen

Studies on Complex Dynamical Systems: Simulations & Theory

State University of New York – University at Buffalo – Dept of Physics

My research group focuses on solving Newton's equations for complex interacting systems.

Sophisticated dynamical simulations carried out at the Center for Computational Research (CCR) of SUNY at Buffalo, which is a world class supercomputing facility, formalism based and ad hoc techniques are used to conduct our research.

<u>We work on the following problems:</u>

- **detection and imaging of shallow buried objects in soil (NSF supported)**
- **shock propagation processes in granular systems (NSF supported),**
- **stabilities and instabilities in granular assemblies,**
- **dust transport, aggregation and filter clogging problems (NASA supported)**

- Kinematic and dynamical simulations of dust transport and dust agglomeration in space and time in microgravity environments.
- Using the simulations as a tool to infer the factors that control dust transport and agglomeration (e.g., electrostatic effects, wind velocity, shapes of particulates) in domestic and in Martian environments.
- Time-dependent degradation of dust filters as functions of dust distributions, filter characteristics and humidity.

Edward Hodgson

Researcher Capabilities Summary

Hamilton Sundstrand Space Systems International

Personal Capabilities

- Extravehicular activity, space life support, thermal control systems design expertise
  - Current and emerging technology base familiarity
  - Space operations knowledge
- Technology and system development
  - Concept development, analysis, laboratory and field test experience
- Systems engineering, system modeling and analysis
- Thermodynamic, heat transfer, fluid flow analyses

Additional Organization Capabilities Available to the Research Program

- Detail design / manufacturing knowledge of EMU, and Shuttle and ISS ECLSS
- Space system materials selection, characterization
- Mechanical design, structural, dynamic, acoustic analyses
- Chemical engineering, catalysis, adsorption, membrane systems
- Electrical design and analysis
- Manufacturing, manufacturability assessment
- Rapid prototyping
- Environmental testing

Masami Nakagawa

Researcher Capabilities Summary

Colorado School of Mines
Mining Engineering Department
PSTG-Space Exploration Program

- ***PI***
- ***Particulate Science & Technology Lab***
- ***Innovative & Exploratory Experiments***
- ***Worldwide Research Network***

- **Fine particle control**
- **Multi-scale mechanical properties**
- **Wave propagation in granular media**
- **Particulate mechanics in extreme environment**
- ***Dust Removal***
- ***Abrasion***
- ***Triboelectrostatic charging***
- ***Segregation***
- ***Acoustic manipulation of fine particles***

Frederick Slane

Space Infrastructure, Inc.

Natural Dust Levitation, Technical Standards

Will investigate and analyze dust levitation due to local and naturally induced electrostatic fields. Establish a direct link to lunar surface electromagnetic field conditions, especially in transition through the terminator. Using previously obtained observational data, will work with space environment investigators to connect space environment models to a 10-meter scale lunar surface environment model. Will connect predicted electrostatic model to hypothetical electromagnetic dust mitigation techniques.

Will use lunar observational data to constrain lunar field conditions for simulation in the lab.

Will document best practices in dust mitigation systems, practices and processes, and work with the open community to establish system and operations standards.

Planetary Geosciences Institute

University of Tennessee – Larry Taylor, Director

State-of-the-art equipment, instrumentation, and lab facilities exist at the University of Tennessee and are available for the scientific and engineering aspects of this proposed endeavor. We have extensive experience working with Apollo soils from all lunar missions and will relate all lunar soil stimulant studies to the ground-truth of the numerous real Apollo soils available in our possession.

Fully automated, Cameca SX-50 Electron Microprobe - forms the basic analytical instrument for most of our geologic and materials research.

Oxford Instrument Energy Dispersive Spectrometer (EDS) Unit on EMP

- **Morphologic & extensive Compositional data acquisition;**
- **X-ray Digital Imaging Analyses** for: 1) of particle types (e.g., lithic fragments, minerals, agglutinates); 2) of typical rock fragments that contribute to the soil; 3) of the actual mineral and glass phases (e.g., pyroxene, agglutinitic glass); and 4) average of each of the different mineral and glass phases (Taylor et al., 1996);
- **Used to fully characterize the fine fractions of numerous Apollo and Luna soils.**

Besides an upgraded **Frantz Isodynamic Separator** for magnetic separation and susceptibility measurements of soil fractions, we also have standard equipment for the preparation of polished thin sections and polished grain mounts of lunar soils and simulants, including a Mo-strip heater, for preparation of fused beads of soil splits for bulk chemical analyses. The equipment necessary for standard soil testing is also available in our labs. In addition, certain soil experiments will be conducted in the laboratories of Dr. Carrier, Director of Micromag Corp. with its sophisticated **"high-gradient magnetic instrumentation",** to pursue the engineering processes for remediation studies involving the magnetic properties of lunar soil. Preliminary experiments using "high-gradient magnetic separation" have demonstrated that highly magnetic lunar dust, when passed through an open matrix of metallic material (e.g., steel wool) inside a powerful magnet, can readily trap fine particles. When the matrix material is "saturated", the magnetic field is turned off, or the matrix is mechanically removed, and the particles fall off. This technique will be investigated as part of an air-filtering system at a lunar base.

Juan H. Agui

Researcher Capabilities Summary

NASA Glenn Research Center

- Experimental measurement techniques in:
  - Turbulent and compressible flows, granular materials flows and mechanics.
- Worked with
  - Laser Doppler Velocimetry (LDV)
  - Particle Image Velocimetry (PIV)
  - Laser Sheet visualization
  - Hot wires
  - Piezo-electric/-resistive sensors
    - Pressure transducers, accelerometers, bending and extension transducers
  - High speed data acquisition
  - High speed cameras
  - industrial vacuum pumps
  - Microscopy
  - Diffusive Wave Spectroscopy (DWS) and other light scattering techniques.
- Developed:
  - Laser vorticity probe
  - Hot wire vorticity probe
  - Drop tower rigs
- Used commercial Computational Fluid Dynamics, CFD, package (Fluent) and developed CFD codes